Numerical simulations of energy transfer in counter-streaming plasmas

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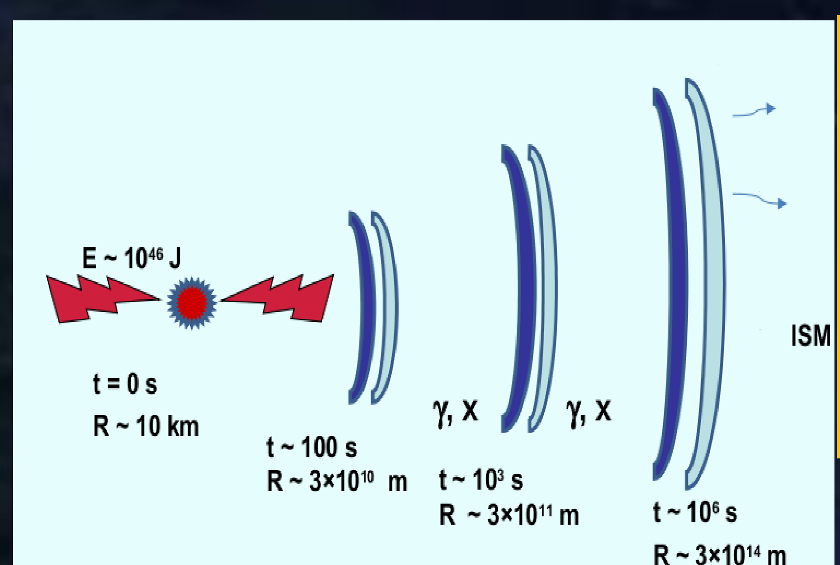
Introduction

Collisionless shocks are frequent events in the universe. They transform energy of star explosion into hot plasma, high energy particules and radiation. It has been shown that the Weibel instability is a very good candidate to explain GRBs [7]. We demonstrate with particle-in-cell simulations that a part of directed kinetic energy of proton beams is converted into energy of electron, ions, electric and magnetic fields [1]. We study the shock structure and energetics of flow and we demonstrate that electron heating is an important catalyst to shock formation via filamentation instability [3], [4].

Colliding plasmas in universe.



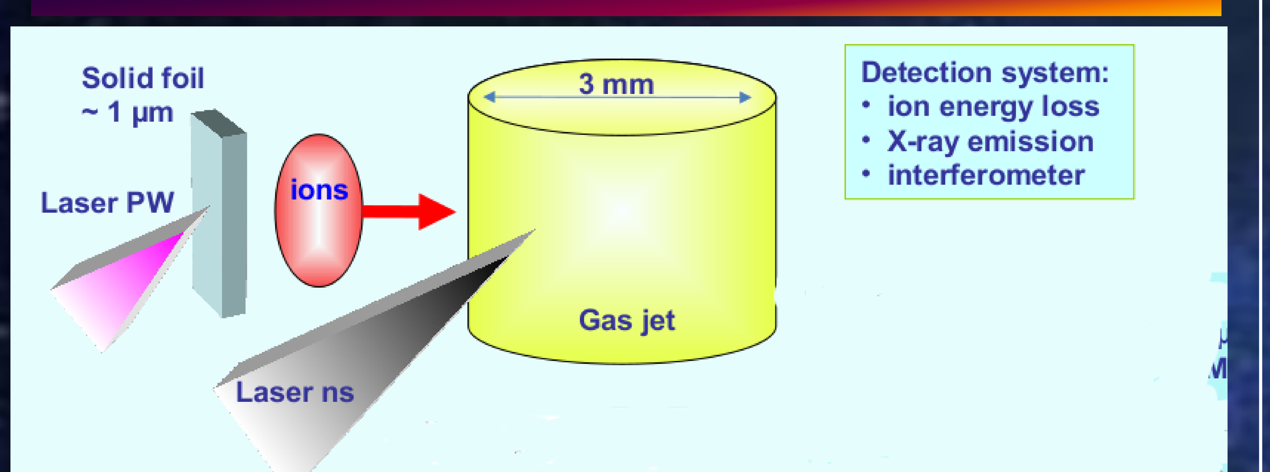
Major hypothesis

_Transformation of the directed energy into thermal energy.

_ Compton and synchrotron emission provides a radiation cooling of plasma [2].

Ejecta from the central explosion : hot plasma.
Interaction with the ISM cold plasma.
Relativstic factor of the jet $\gamma = 100$ explains the short pulse duration recorded by observers [2],[4].

Modeling shocks in astrophysical laboratories



Scheme of laboratory experiment on the collisionless dissipation of fast ion beams [1].

1_ A proton bunch is created from a thin foil irradiated by a high intensity short laser pulse.

2_ Transport zone of the proton bunch to the interaction site.

3_ Target plasma created by ionization of a gas jet with an auxiliary laser beam.

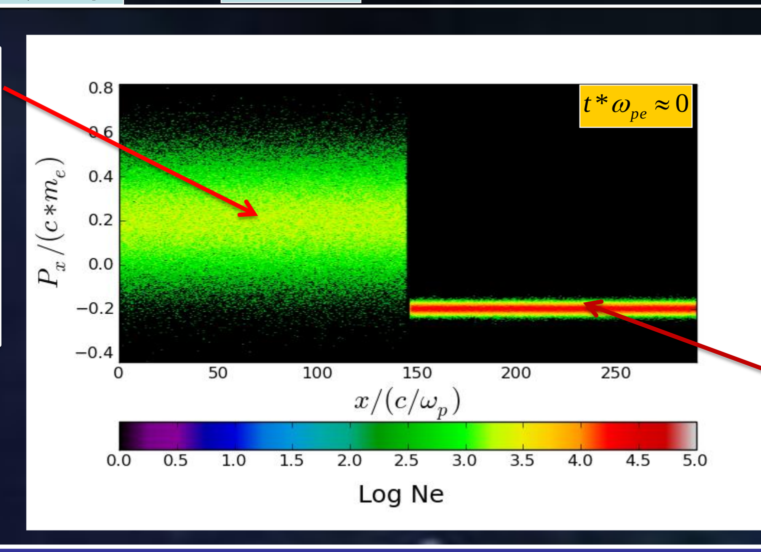
4_ Diagnostic equipments : ion energy detector, interferometer x-ray detector.

PIC simulations of sub-relativistic plasmas

We present here an analysis of a very large PIC simulations of two inter-penetrating plasmas at sub-relativistic velocities. At the initial time moment in the center-of-mass reference frame two homogenous plasmas of the density $n_0 = 10^{-18} cm^{-3}$ are facing each other in the simulation plane (x,y).
All lengths are measured in terms of electron inertia length, c/ω_{pe} , the time is in inverse electron plasma frequencies, ω_{pe}^{-1}, the energy is measured in units of electron rest energy, $m_e c^2$,the electric and magnetic fields is are in relativistic plasma units, $\tilde{E} = eE/m_e\omega_{pe}c$, and $\tilde{B} = eB/m_e\omega_{pe}$, respectively.

Hot plasma jet 10keV representing the particles of the core engine.

$u_p = 0.2c$



Cold plasma 100 eV representing the ISM

$u_p = -0.2c$

We use the 2D version of PICLS.
For these kind of numerical simulation we use at least :160 cores, 14500 *1600 cells of plasma , 32 of macro-particules per cell.
the time step is $\Delta t = 0.1/\omega_{pe}$ .Time computation is typically 2 weeks.

Temporal development of inter-penetrating plasmas

First stage of interaction
electron instability [2],[3]

$$u > v_{Te} \quad \gamma \simeq \omega_{pe}(m_e/m_i)^{1/3} \quad \vec{k} \parallel \vec{u} \parallel \vec{E}$$

$$u < v_{Te} \quad \gamma \simeq \omega_{pe} u/c \quad \vec{k} \perp \vec{u} \parallel \vec{E}$$

Second stage of interaction
Ion-electron instability [2],[3]

$$u < v_{Te}, \quad \gamma \simeq \omega_{pi} u/c, \quad \vec{k} \perp \vec{u} \parallel \vec{E}$$

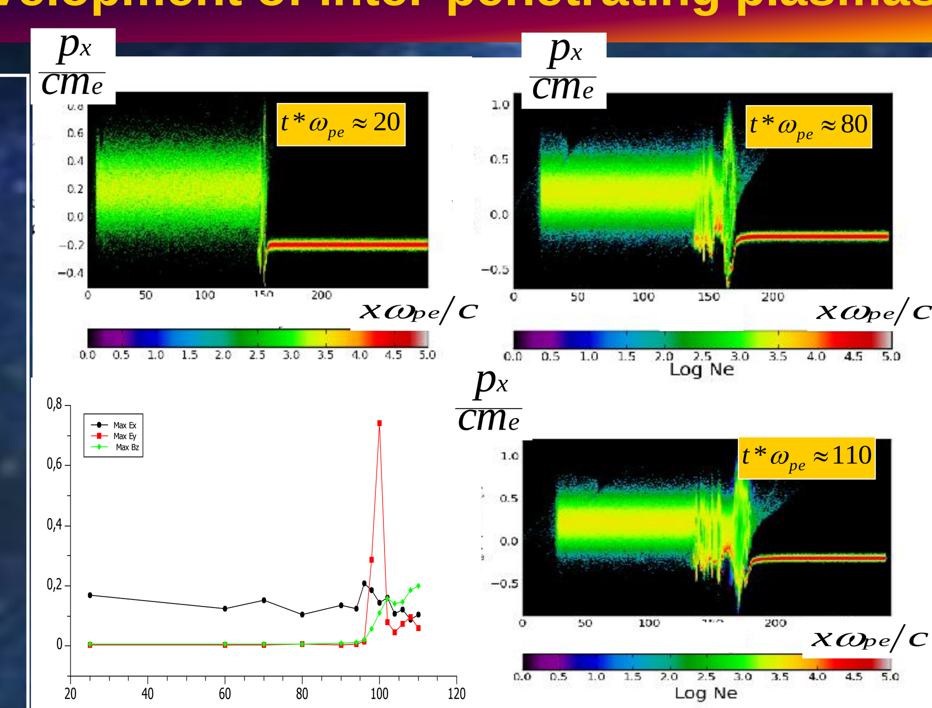
The electron vortex is attached to the edge of the hot plasma and increases in size.

Electron mixing and heating in parallel direction stabilizes the two-stream instability but excites the Weibel instability in the transverse direction.

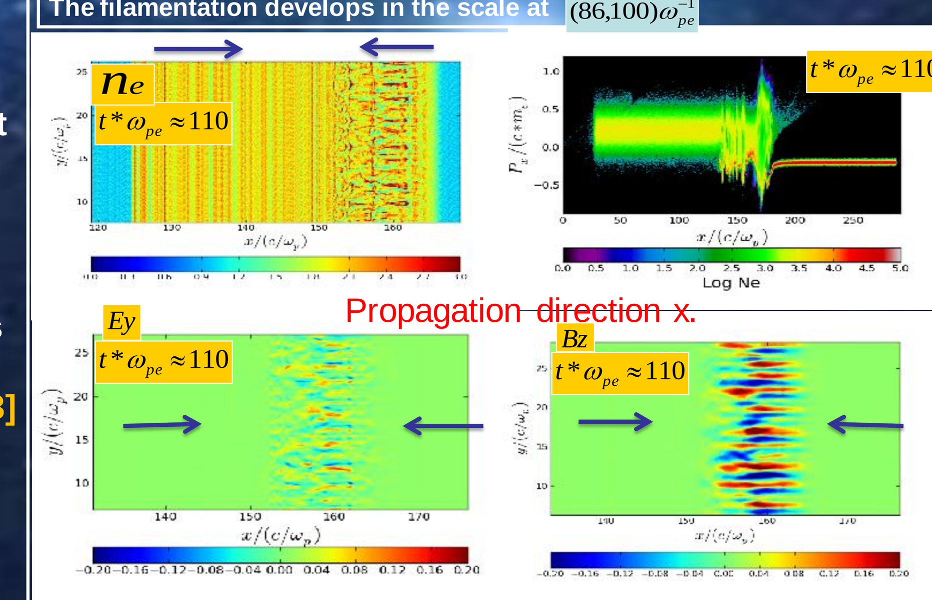
The caracteristic field is defined by the relative electron-ion motion [2],[3]

$$\gamma \approx \omega_{pe}\left(\frac{m_e}{m_i}\right)^{1/3} \quad k_x \approx \frac{\omega_{pe}}{u}$$

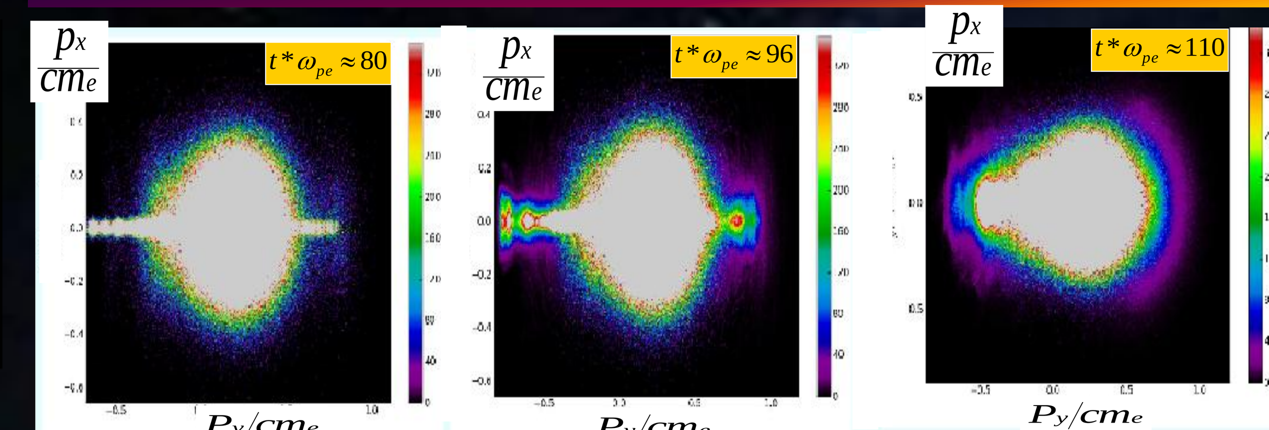
$$\frac{eE_x}{m_e\omega_{pe}c} \approx 0.6\frac{u}{c}$$



The sequence of instability can be seen in the temporal evolution of the fields.
The electron two-stream instability develops in the time scale $(10,20)\omega_{pe}^{-1}$
The filamentation develops in the scale at $(86,100)\omega_{pe}^{-1}$



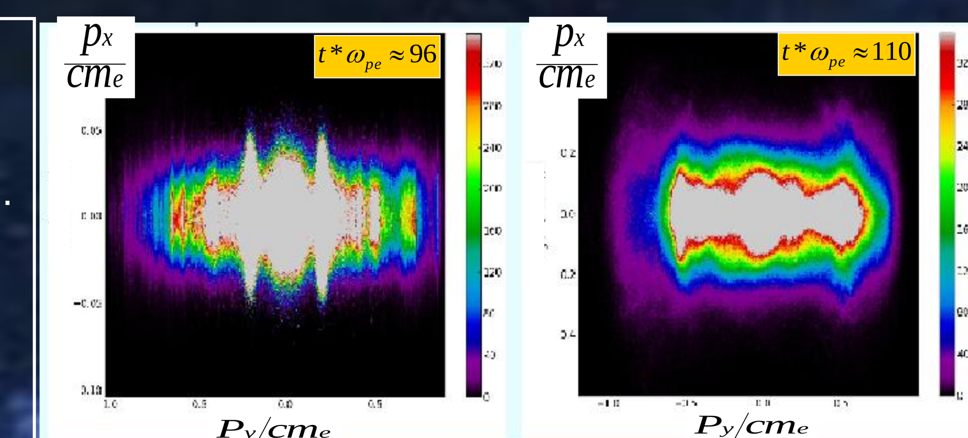
Distribution functions of the electrons. Asymetric case 10 keV / 100 eV



Distribution functions of the electrons. Symetric case: two cold plasmas 100 eV.

Energy transfer in the transverse direction and heating of electron.

Weibel instability leads to electron heating in the transverse direction.

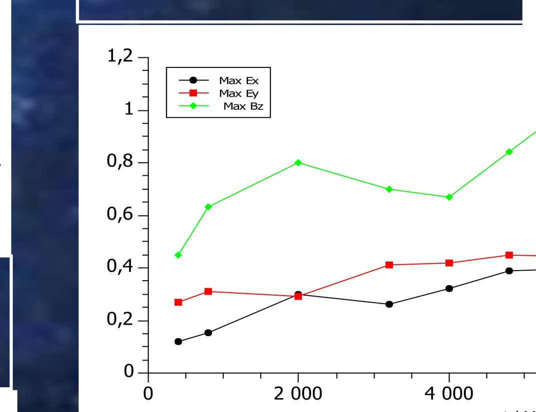


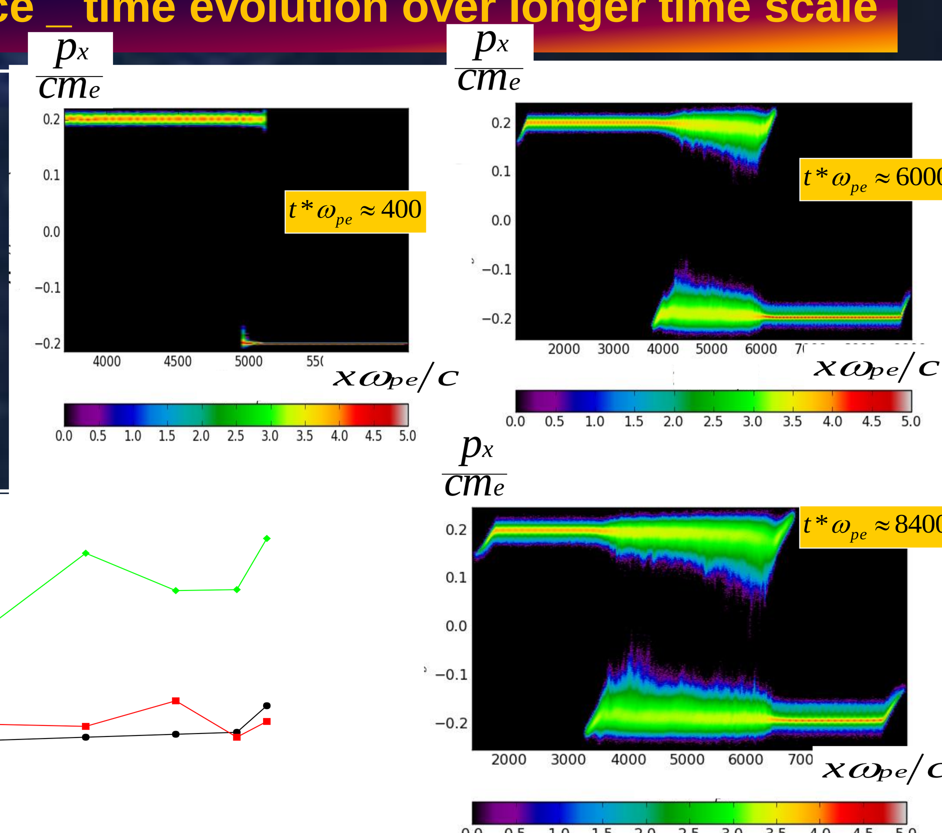
Ions phase space _ time evolution over longer time scale

Mass ration of electrons

$$\frac{\omega_{pe}}{\omega_{pi}} \approx \sqrt{\frac{m_i}{m_e}} \approx 42.84$$

The ion motion starts on a longer time scale, and they lose 10% of their energy at $200\omega_{pi}$



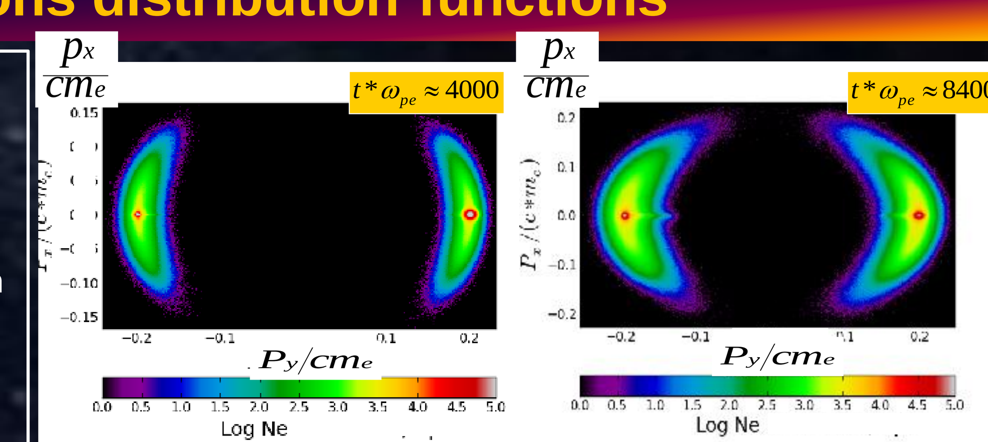


Ions distribution functions

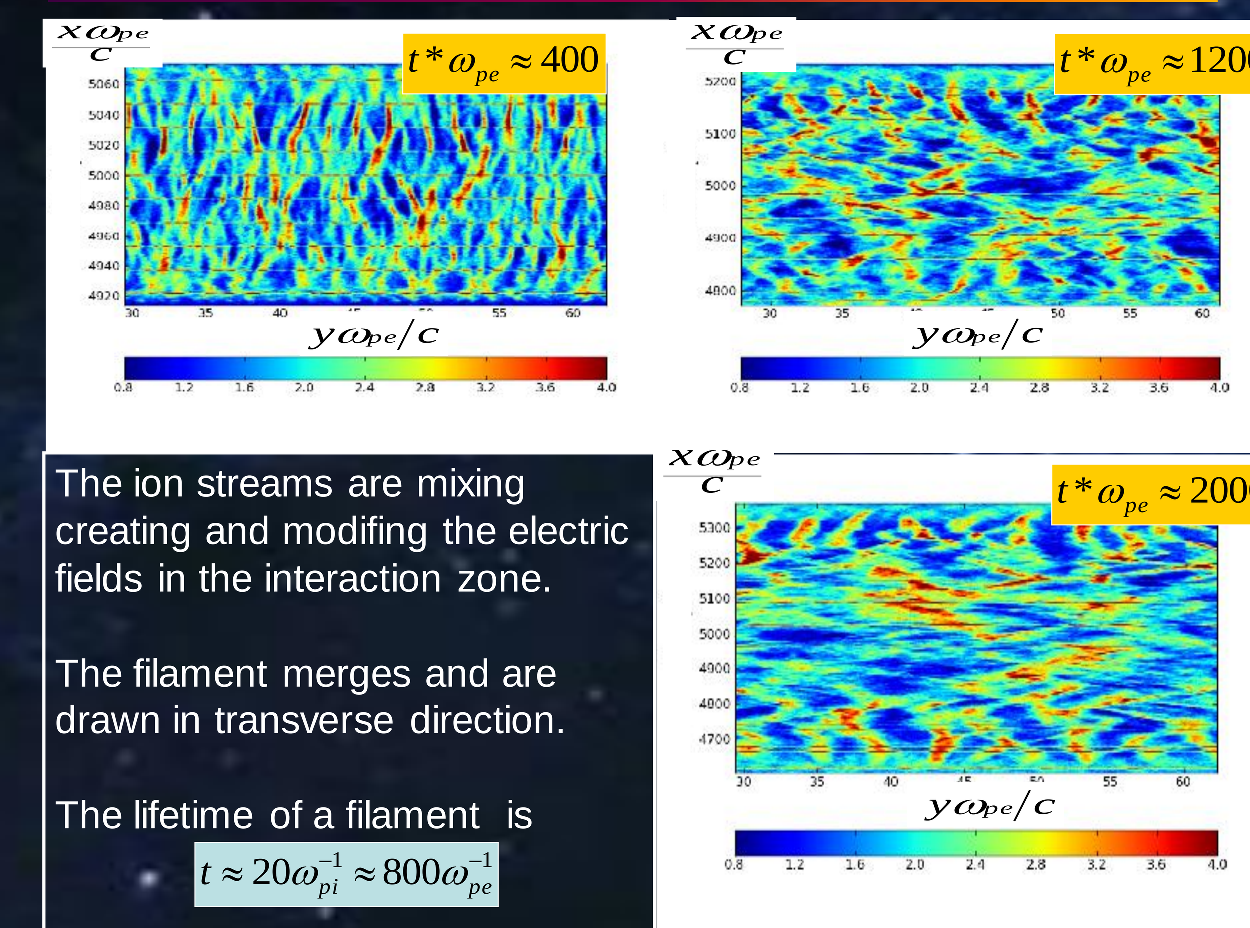
The electric field amplitude decreases .

magnetique field becomes dominant with the time.

Ions are stopped on higer scale of time.



Evolution of filaments



The ion streams are mixing creating and modifing the electric fields in the interaction zone.

The filament merges and are drawn in transverse direction.

The lifetime of a filament is

$$t \approx 20\omega_{pi}^{-1} \approx 800\omega_{pe}^{-1}$$

Very high energy of electrons in the filament.

Strong electrostatic field due to the charge separation.

Conclusion

An experiment for studying the collisionnelss mechanism of fast ion energy in laboratory plasma is proposed. We have performed two dimensional PIC simulations of electron-ion sub-relativistic counter-streaming plasma beams propagating without an external magnetic field. Electron heating is an important stage of shock formation. This is probably due to stochastic processes that occurs due to the strong charge separation. Radiation emission losses is due to electron synchrotron emission [7]. Simulations of similar physical processes at the GRB scale are ongoing.

References

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